United States
Department of
Agriculture

Forest Service

Pacific Northwest
Forest and Range
Experiment Station

Research Paper
PNW-341
July 1985

Height Growth and Site Index Curves for Douglas-Fir on Dry Sites in the Willamette National Forest

Joseph E. Means and Mary E. Helm

Authors

JOSEPH E. MEANS is a research forester at the Pacific Northwest Forest and Range Experiment Station, Forestry Sciences Laboratory, 3200 Jefferson Way, Corvallis, Oregon 97331. MARY E. HELM is a research assistant at the Department of Forest Science, Oregon State University, Corvallis, Oregon 97331.

Cover Photo

Reference stand 20 on the H.J. Andrews Experimental Forest is characteristic of the *Pseudotsuga menziesii/Holodiscus discolor/*grass plant community, *Colomia heterophylla* phase, that was sampled in this study.

Abstract

Means, Joseph E.; Helm, Mary E. Height growth and site index curves for Douglas-fir on dry sites in the Willamette National Forest. Res. Pap. PNW-341. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 17 p.

Equations and curves are presented for estimating height and site index of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) on hot, dry sites in the Willamette National Forest in western Oregon. The equations are based on the dissected stems of 27 trees. The curves differ from those previously published for Douglas-fir. Instructions are presented for their use.

Keywords: Increment (height), site index, Douglas-fir, Oregon (Willamette National Forest).

Research Summary

This study provides height growth and site index curves for Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco) on hot, dry sites in the Willamette National Forest in western Oregon. Stems of 40 trees were dissected; 27 of the trees were suitable for construction of height growth and site index curves, and they provided 505 observations of height, site, and age.

Smoothed height growth curves developed from these data were compared with published Douglas-fir height growth curves. Because the published curves could not adequately describe height growth patterns of these trees, new height growth and site index curves were constructed.

Four estimating equations for height growth and three for site index were fitted by use of weighted least squares regression, and site index and height were constrained to be equal at index age, 100 years. The equations with the best fit to the data across the ranges of age and site index were chosen as the final models. The resulting curves differ from those previously published for Douglas-fir.

Instructions for using the equations are presented.

Contents

1 **Introduction**
2 **Field Methods**
2 Study Area
2 Tree Selection
2 Stem Dissection
2 **Data Preparation**
2 Ring Counting
3 Data Cleaning and Screening
5 **Analysis**
5 Examination of Available Curves
6 Choice of Index Age
6 Weighted Regression
6 Constraining the Models
6 Construction of Height Growth Curves
8 Construction of Site Index Curves
11 **Discussion**
11 Comparison With Other Height Growth Curves
13 Reliability
15 **How To Use the Equations**
15 Stand Selection
15 Tree Selection
15 Equations for Total Height in Feet
16 **Acknowledgments**
16 **English Equivalents**
16 **Literature Cited**

Introduction

In the western Cascade Range of Oregon and Washington, height growth and site index curves are available for Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco) on mesic, midelevation sites (McArdle and others 1961, King 1966), and on upper slopes near the cool extreme of its range (Curtis and others 1974b). No height growth or site index curves have been available, however, for Douglas-fir near the relatively hot, dry extreme of its range in the western Cascades. Height growth of Douglas-fir is slower initially but is more prolonged on such dry sites than on moister sites (Means 1980), and as a result volume growth follows a similar trend. Thus, available site index curves (for example, McArdle and others 1961, King 1966), yield tables (for example, McArdle and others 1961, Curtis and others 1982), and height growth curves in stand growth simulators (for example, DFSIM by Curtis and others 1981) are not applicable. The objective of this study was to construct height growth and site index equations for Douglas-fir on hot, dry sites in the Willamette National Forest in Oregon.

Curves that reach well beyond 200 years are needed for estimating site index for old stands and for estimating height at advanced ages to evaluate the effects of management of stands for old-growth characteristics.

Several methods have been used in constructing Douglas-fir height growth and site index curves. McArdle and others (1961) built height growth curves from many one-time observations of height and age, fitting a mean guide curve, then making other curves proportional to the guide curve. This technique, however, includes several sources of significant error that can be eliminated by using stem dissection data (Curtis 1964). King (1966) used stem dissection data to construct height growth curves for Douglas-fir with height as the dependent variable and then used these curves to estimate site index. Site index estimating equations, however, should be fit with site index as the dependent variable, and height growth estimating equations should be fit with height as the dependent variable (Curtis and others 1974a). Curtis and others (1974b) built upper-slope Douglas-fir height growth and site index curves in this way. Dahms (1975) built on this basic idea by first fitting, for decadal ages, linear regressions to estimate site index ($SI = a0 + a1\ HT$) and height ($HT = b0 + b1\ SI$), then building age back into the models by defining the slopes of these regressions and the mean height curves in terms of age; Dahms worked with lodgepole pine (*Pinus contorta* Dougl. ex Loud.). Cochran (1979) used Dahms' technique to build curves for Douglas-fir in eastern Oregon and Washington. Monserud (1984) found Dahms' technique suitable as a first step in deriving a site index estimating equation, but inferior to a logistic equation for describing height growth of Douglas-fir in the northern Rocky Mountains. As a final step, Monserud (1984) eliminated highly correlated terms from the site index equation without degrading model fit. The equation forms used for Douglas-fir by the above investigators were examined in this study.

Field Methods

Study Area

This study was a component of a larger study in the Detroit, Blue River, McKenzie, Oakridge, and Rigdon Ranger Districts of the Willamette National Forest (Means 1980). Trees were cut in all these Districts except Detroit, where dry coniferous forest is relatively limited in extent, so suitable sampling sites could not be found (fig. 1).

Trees were cut from dry coniferous forests, defined as climax Douglas-fir and incense-cedar (*Libocedrus decurrens* Torr.) and lacking significant (0.1 percent cover) western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) in any size class. These dry-site Douglas-fir community types (Means 1980) are more similar to the *Pseudotsuga/Holodiscus* type than to any other community type of Dyrness and others (1974).

Tree Selection

Several criteria were used for selecting trees. Candidate trees were dominants or strong codominants with straight boles and no sign of top breakage. Unhealthy crowns, flat or deformed tops, or several conks (or one large conk) were causes for rejection. Candidates were increment bored at breast height. Trees showing periods of suppressed radial growth or significant rot were not used. These criteria for increment cores resulted in rejection of 70 to 90 percent of the trees more than 200 years old, and 30 to 70 percent of the trees 100 to 200 years old that met the exterior criteria. Effects of past fires (scars and resultant butt rot), top breakage, and disease increase with age. Suppressed radial growth was a common cause for rejection, which is not surprising because canopy trees often become established in stands with mature trees (Means 1982). Many plots in stands with canopy trees more than 200 years old contained no trees suitable for dissection (and therefore none suitable for estimation of site index). The high rate of rejection precluded assessment of the potential bias in site index curves caused by changes in the tallest tree on a plot through time (Dahms 1963).

Stem Dissection

The stems of 40 trees on thirty-six 0.1-ha plots were dissected; in general, the techniques of Herman and others (1975) were followed. In most cases cross-section disks were cut at stump height, at breast height (137 cm above ground level), and at 2-m intervals above breast height. Ground level was defined as the mean of the ground levels on the uphill and the downhill sides of the tree. In 1977 whole disks were taken to the laboratory, and narrow (approximately 2 x 2 cm) sections, the length being the distance from the edge to the pith of the disk, were cut with a table saw. Cutting these narrow sections precluded cross-checking ring counts on additional radii. Therefore, in 1978 wider sections (10 to 20 cm) were cut from disks in the field with a chain saw; and whole disks were usually collected at stump and breast height.

Data Preparation

Ring Counting

The narrow sections from trees cut in 1977 were prepared by sanding. The wider 1978 sections were prepared with a belt sander if the wood was dry or with a "Surform"[1] plane if the wood was moist. Narrow rings (less than about 1 mm) were sanded and were counted under a binocular microscope with variable magnification. Maintaining standing water along radii improved our ability to distinguish rings but was seldom done because it was difficult to sustain for more than a minute. Usually two radii were counted at each disk height.

[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

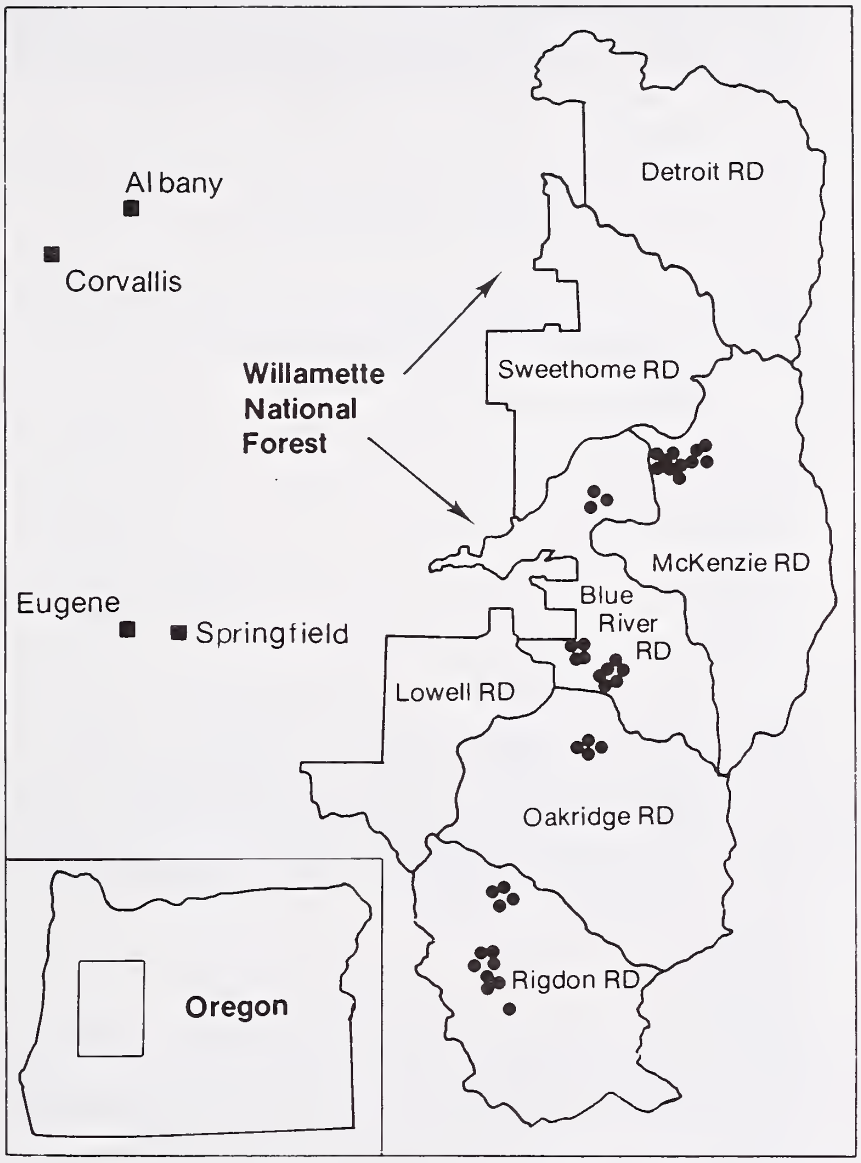

Figure 1.—Locations of sample trees (●) in the Willamette National Forest (RD is Ranger District).

Data Cleaning and Screening

Height versus age was then plotted for each tree. Anomalies such as abrupt changes in height growth rate were often corrected by recounts or counts of new radii on whole sections. A program written in FORTRAN 77, STEM, was used to plot height over age and height growth rate for each tree and to calculate (by linear interpolation) heights at decadal ages for fitting height growth and site index models.

Ten trees showed suppressed height growth early in life or had isolated periods of relatively slow height growth, indicating significant top breakage or suppression. These were excluded from further analysis. Two trees with breast-height age less than 100 were too young to be used for constructing site curves with an index age of 100 and were also excluded. After these trees were rejected, only one 0.1-ha plot remained with two trees. Height growth curves for these trees did not cross, so their decadal heights were averaged and treated as one tree. The height growth curves of two trees were truncated to eliminate height growth anomalies at advanced ages. The analyses thus were based on 27 trees and 505 observations of: height above breast height, site index (height above breast height at 100 years breast-height age), and decadal breast-height age. These trees are summarized by site index class, breast-height age, and topographic position in table 1, and by dry-site plant community in table 2.

Table 1—Distribution of the 27 Douglas-fir trees used in analyses, by breast-height age, elevation, slope, and aspect for ranges of site index

Stratum	Range of site index (meters above breast height, index age 100)						
	26-30	30.1-34	34.1-38	38.1-42	42.1-46	46.1-50	All site indices
	Number of trees						
Breast-height age (yr):							
100-150			1	5	2	2	10
151-200			1	2			3
201-250	1	2	1	1			5
251-300	2	4	1	2			9
	Years						
Mean age	240	263	200	172	122	112	194
	Number of trees						
Elevation (m):							
500-599	1		1	1			3
600-699	1			2	1		4
700-799	1	5	2	4			12
800-899		1		1	1	2	5
900-999			1	2			3
	Meters						
Mean elevation	631	779	760	776	771	899	767
	Number of trees						
Slope (percent):							
0-20				1			1
21-40	1	2	1	1			5
41-60	2		2	4	1		9
61-80		2		4	1	2	9
81-100		2	1				3
	Percent						
Mean slope	39	62	50	53	58	67	54
	Number of trees						
Aspect (degrees):							
91-180			2	3	1		6
181-270	3	6	2	6		2	19
270-360				1	1		2
Total trees	3	6	4	10	2	2	27

Table 2—Distribution of the 27 Douglas-fir trees used in analyses, by plant community for ranges of site index

Plant community 1/	Range of site index (meters above breast height, index age 100)						
	26-30	30.1-34	34.1-38	38.1-42	42.1-46	46.1-50	All site indices
	Number of trees						
Psme/Hodi/grass:							
Asde phase	1						1
Cohe phase	2		1	1			4
Psme/Hodi-Acci	1		1	2	1	2	7
Psme/Beaq/Dispo	1	2	1	1			5
Lide/Whmo				2			2
Lide/Chum		2	1	3	2		8

1/ Plant communities are described by Means (1980). The species codes are: Acci = *Acer circinatum*, Asde = *Aspidotis densa*, Beaq = *Berberis aquifolium*, Chum = *Chimaphila umbellata*, Cohe = *Collomia heterophylla*, Dispo = *Disporum* spp., Hodi = *Holodiscus discolor*, Lide = *Libocedrus decurrens*, Psme = *Pseudotsuga menziesii*, Whmo = *Whipplea modesta*.

Analysis

Examination of Available Curves

Because our data set is small (27 trees) it was important to determine as a first step whether new curves were really needed or whether existing Douglas-fir curves would suffice. Toward this end, we compared our height growth curves, smoothed using Heger's (1968) data summarization method (at site indices of 28, 32, 36, 40, and 44 m), with the height growth curves published by Curtis and others (1974b), Monserud (1984), King (1966), and Cochran (1979). Site indices for these curves were chosen so they would cross our curves at their index ages.

The height growth curves of King (1966), Cochran (1979), and Monserud (1984) were consistently biased compared with ours; they had higher values for height before their index age (50 yr) and lower values past this age. At age 120, discrepancies were 2.5 to 3.5 m for Cochran's, 4 to 6.5 m for King's, and 3 to 7.5 m for Monserud's. These discrepancies consistently increased past age 120, especially for Cochran's (1979) height curves which declined past age 180–an extrapolation past his data that extended to 130 years.

Curtis and others' (1979b) upper-slope Douglas-fir height growth curves are closer to ours in a narrow range of moderate site indices (32-36 m), where errors are all less than 2 m (within the range of our data). At low sites indices, however, our dry-site trees grow more slowly initially and more rapidly at advanced ages than do upper-slope Douglas-firs. At high site indices, conversely, our trees grow more rapidly initially, and more slowly later than do upper-slope Douglas-firs. Errors range from -1.5 to 2.2 m for trees less than 100 years old and from -2.7 to 3.0 m for trees older than 100 years. The dry-site Douglas-fir height growth curves are more polymorphic than the curves for upper-slope Douglas-fir.

Because height growth curves derived by Heger's (1968) method differed from those already available, our site index curves for Douglas-fir on hot dry sites would also be different; therefore we decided to build new curves even though our data set was small.

Choice of Index Age

An index age of 100 years at breast height (1.37 m) was chosen because this will probably be near rotation age in managed stands of this type, and the reliability of site index estimates should be better than it would be if a younger index age were chosen. Site index estimates are less accurate when differences between stand age and index age are relatively large, and many dry coniferous forest stands are 100 to 250 years old.

Weighted Regression

All height growth and site index models were fitted by weighted least squares regression since variance was not uniform across the range of ages. The iterative weighting technique of Monserud (1984) was used, in which the weight was the inverse of the variance at each decadal age.

Constraining the Models

Height growth models were constrained so that trees "grown" in computer models will reach a height equal to known site index at index age. For all (except one) height growth models, HT = f(SI,age), height (HT) was constrained to equal site index (SI) at index age by subtracting SI = f(SI,index age) from the height model before fitting, giving HT = SI + f(SI,age) – f(SI,index age) (the model of Curtis and others (1974b) was constrained using the technique they describe). Site index models, SI = f(HT,age), were similarly constrained so that trees measured in the field at the index age would have current height as their site index. Errors up to 0.5 m at index age would occur if equations were not constrained. Constraining typically reduced divergence from Heger's (1968) curves (see below) within the range of most of our data and rarely degraded the fit.

Construction of Height Growth Curves

Heger's curves.—The first step in construction of height growth curves was to fit, individually for decadal breast-height ages, linear regressions of height on site index (Heger 1968) of the form

$$HT = a + b\,SI; \qquad (1)$$

where HT = total height - 1.37 m (height above breast height), SI = HT at 100 yr, and a, b = regression coefficients. A total of 28 regressions were fit, for decadal ages 10 to 280. Examination of the data and residuals showed no curvilinear trends at any age. We constructed height-over-age curves (fig. 2) from this family of 28 regressions and compared them with candidate height growth curves to aid in model selection. Heger (1968) used such curves as height growth curves, but we derived a more general equation because these were unrealistically jagged at advanced ages, and to provide one equation for use in computer programs.

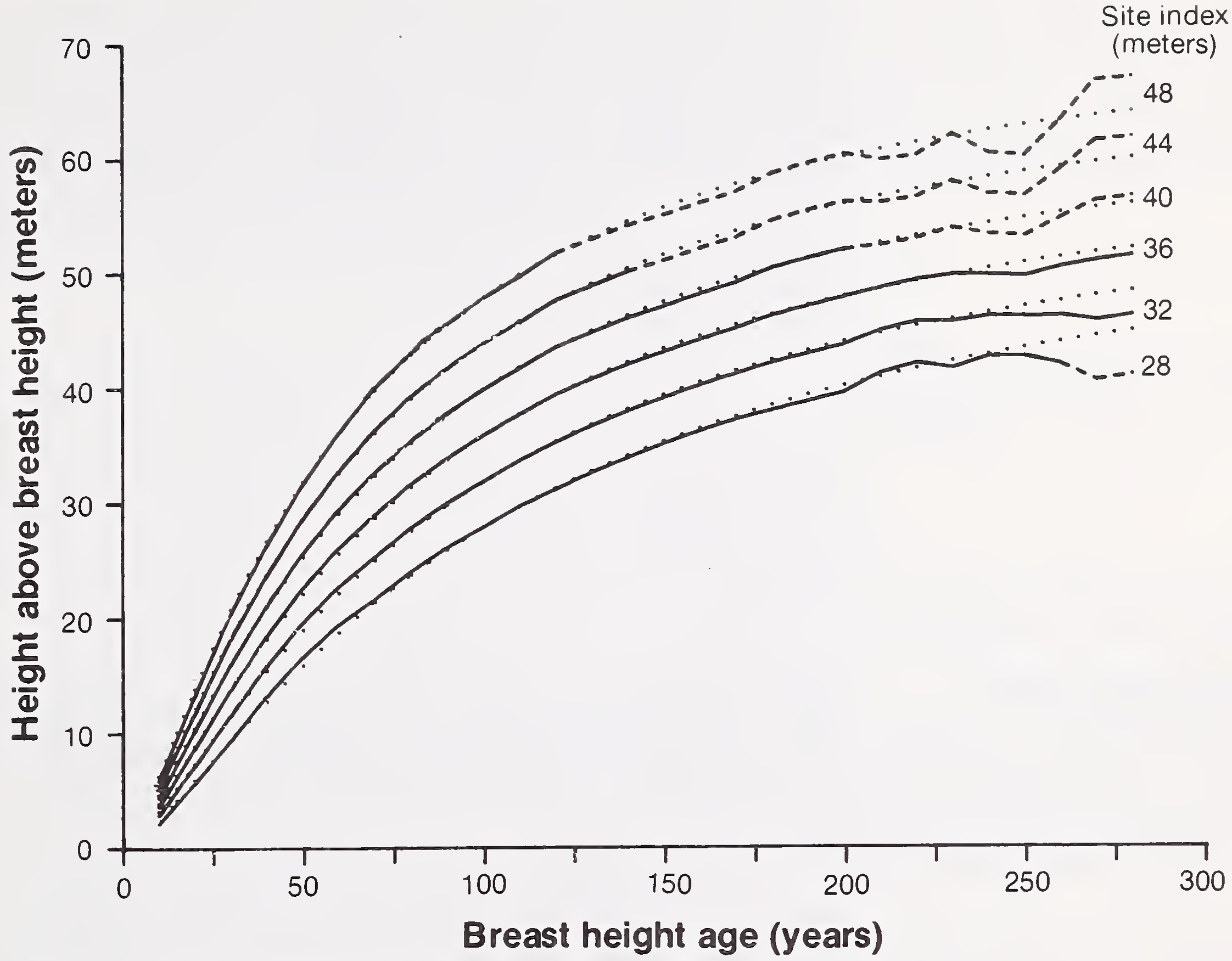

Figure 2.—Height growth curves based on Heger's (1968) family of regressions, equation (1)—solid and dashed curves (dashes indicate points beyond the data); and the final height growth model, equation (6)—dotted curves.

Choosing the height growth model.—Four height growth models were examined. The model used by Curtis and others (1974b), rewritten to express height as a function of site and age, is

$$HT = SI/(a + bA^n + cA^n/SI); \tag{2}$$

where a, b, c, n = regression coefficients and A = breast-height age. The model King (1966) used was examined,

$$HT = A^2/(a + bA + cA^2); \tag{3}$$

where a, b, c = functions of SI. The equation used by Beck (1971) is

$$HT = a\,(1 - \exp(bA))^c; \tag{4}$$

where a, b, c = functions of SI and exp(bA) is the base of the natural logarithm to the power bA. The model form used by Monserud (1984) was also fit,

$$HT = a\,SI^b/(1 + \exp(c + d\ \ln A + e\ \ln SI); \tag{5}$$

where a, b, c, d, e = regression coefficients.

Each model was first fit to the smoothed height over age curves derived by Heger's (1968) method, equation (1). At all but the lowest site index levels, model (5) underestimated height at low ages and overestimated it at high ages so it was not examined further. The remaining models were fit to the decadal heights and ages, and they gave nearly identical fits—standard errors of the estimates (SEE's) ranged from 1.73 to 1.76 m. Examination of residuals showed no problems with bias. Equation (2) was chosen because it had a simpler form; the coefficients of equations (3) and (4) were functions of site index with two or three terms each. Its final form after it was constrained (Curtis and others 1974b) was,

$$HT = SI/(d + b\,A^n + e/SI + c\,A^n/SI); \tag{6}$$

where HT, SI, and A are defined as for equations (1) and (2); d = 0.90031; b = 36.932; e = -11.9659; c = 4433.1; and n = -1.28438; with an SEE of 1.73 m. Height growth curves based on equation (6) and on Heger's regressions, equation (1), are shown in figure 2.

Construction of Site Index Curves

Heger's curves.—The first step in construction of site index curves, similar to that for height growth curves, was to use Heger's (1968) method to fit, individually for decadal ages, linear regressions of site index on height of the form,

$$SI = a + b\,HT; \tag{7}$$

where a, b = regression coefficients. Examination of the data and residuals showed no curvilinear trends at any age. Inverse estimates of height for several levels of site index were calculated and used in plotting these relationships in the traditional height over age format. The linear regressions, equation (7), and the height over age curves were compared graphically with candidate site index estimating equations to aid in model selection.

Constructing and choosing the site index model.—Three site index estimating equations were examined. The first model was a generalized form of equation (7) (Curtis and others 1974b),

$$SI = a + b\,HT; \tag{8}$$

where a, b = functions of breast-height age. Stepwise regression was used to select from many independent variables for describing a and b. Monserud (1984) derived a site index model by first constructing an equation by Dahms' (1975) method, then removing highly correlated terms and recalculating least squares parameter estimates. His final model was the second model examined here:

$$SI = a + b\,(\ln A)^2 + c\,A\ln A + d\,HT + e\,HT/A; \tag{9}$$

where a, b, c, d, e = regression coefficients. The third model, constructed by Dahms' (1975) method, involves finding a function of breast-height age (A) for b in equation (8),

$$b = f_b(A), \tag{10}$$

and fitting an equation to mean decadal height (MHT),

$$MHT = f_{mht}(A). \tag{11}$$

When fitting equation (11), we wished to maintain MHT at the same mean site index (MSI = 37.312 m) for all decadal ages. Therefore, when trees dropped out at advanced ages, we estimated MHT from Heger's regressions, equation (7), at SI = MSI. Then MHT was substituted for HT, and MSI (MSI can be considered constant with age since older MHT's were adjusted to it) was substituted for SI in equation (8), which was solved to provide an equation for a:

$$a = MSI - b\ MHT. \tag{12}$$

Substituting equation (11) for MHT in equation (12), then substituting equation (10) for b and the modified equation (12) for a in equation (8), and simplifying, gave a smoothed site index estimating equation of the type used by Dahms (1975):

$$SI = MSI + f_b(A)\ (HT - f_{mht}(A)). \tag{13}$$

This equation was constrained to pass through HT = SI at index age, which eliminated the constant MSI; and new parameters were estimated by least squares to improve its fit.

Height over age curves for each site index model were compared with Heger's curves from equation (7), and plots of the "residuals" (difference) between each model and Heger's curves were examined. Plots of site (predicted, actual, and Heger's) over height and their residuals for alternate decadal ages were also examined. Problems with bias became readily apparent, which facilitated rejection of some models and simplified selection of equation (13) as the final model.

Attempts to reduce the number of coefficients of equation (13), as Monserud (1984) did, markedly reduced the fit, so all fitted coefficients (b-g) were retained. After equation (13) was constrained and simplified it became

$$SI = (b + c\ A + d\ A^{-0.5})\ (HT - 1/(e + f\ A^{g})) + k\ HT + j; \tag{14}$$

where SI, HT, and A are defined as for equations (1) and (2), b = 0.94622, c = -0.00175322, d = 3.6660, e = 0.0168601, f = 2.7676, g = -1.19554, k = -0.137502, and j = 40.470. Site index curves based on this equation are presented in figure 3 and are compared with those based on Heger's regressions, equation (7), in the more familiar inverted form in figure 4.

The final height growth and site index curves are compared in figure 5.

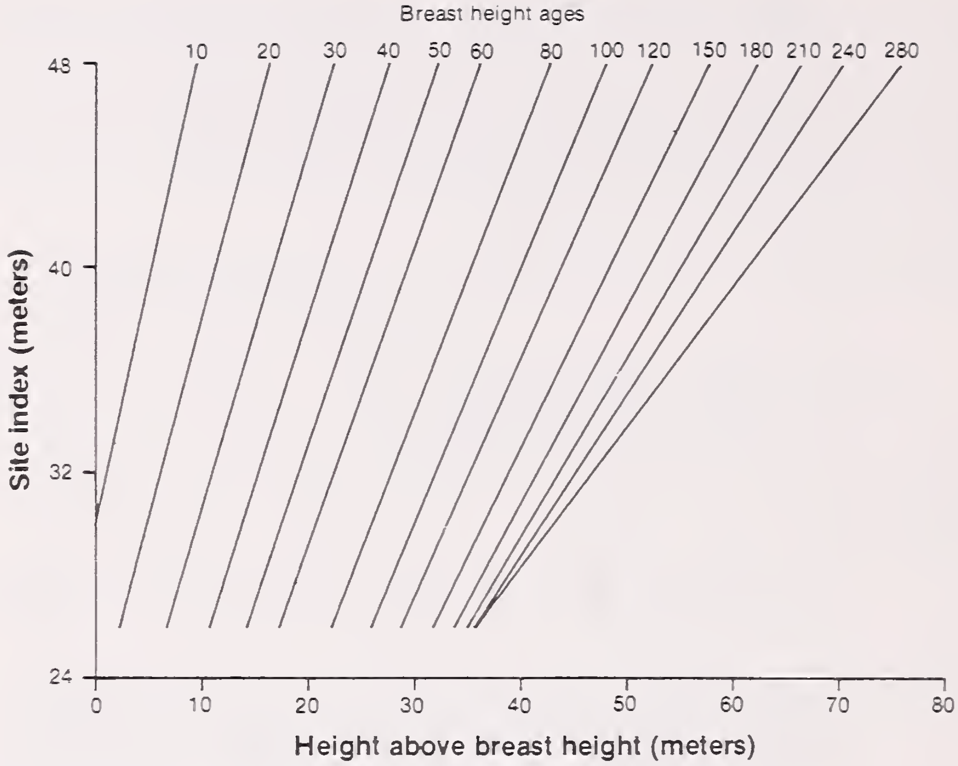

Figure 3.—Final site index estimating curves, equation (14), presented with the dependent variable (site index) on the vertical axis.

Figure 4.—Site index curves based on Heger's (1968) family of regressions, equation (7)—solid and dashed curves (dashes indicate points beyond the data); and the final site index model, equation (14)—dotted curves.

Figure 5.—Comparison of final height growth (solid curves) and site index curves (dashed curves).

Discussion

Comparison With Other Height Growth Curves

The final height growth curves, equation (6), are compared with other height growth curves for Douglas-fir in figure 6. The curves of McArdle and others (1961) for western Washington and Oregon, King (1966) for Washington, Cochran (1979) for eastern Washington and Oregon, and Monserud (1984) for the northern Rocky Mountains all show more rapid height growth at early ages and slower height growth later than do the curves for dry-site Douglas-fir. One important implication is that volume growth in dry-site Douglas-fir stands is initially slower but is more prolonged and maximum mean annual increment occurs later than in the other forest types studied (Means 1980).

Height growth of upper-slope Douglas-fir in the Washington and Oregon Cascade Range (Curtis and others 1974b) is similar to that on dry sites at midsite indices (fig. 6a). At higher site indices, however, height growth on dry sites is initially faster but is slower later in life, whereas at lower site indices it is initially slower but is faster later in life.

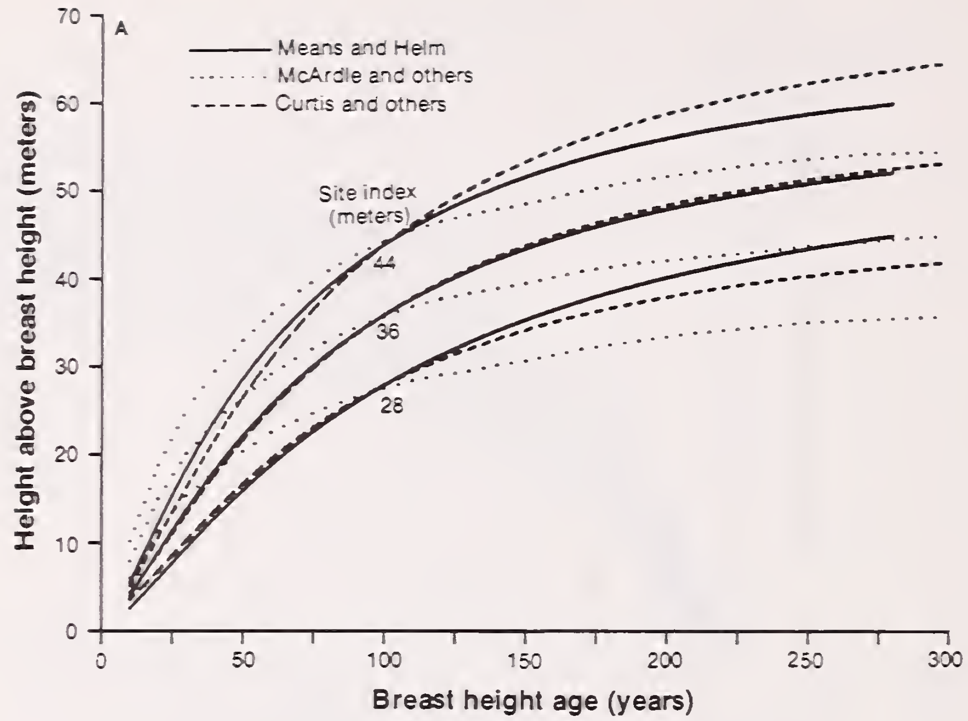

Figure 6.—Comparison of our height growth curves, equation (6), with height growth curves previously published for Douglas-fir. Site indices for these curves were chosen so they would cross our curves at their index ages: A, comparison of our curves with those of Curtis and others (1974b) and McArdle and others (1961); B, comparison of our curves with those of Cochran (1979), King (1966), and Monserud (1984).

Reliability

The reliability of all predicting equations is strongly influenced by the unexplained variation in the data used to build the equations. The variation the final models cannot explain is expressed as the standard error of the estimate (SEE) in figures 7 and 8. Estimates are less reliable when the SEE is greater.

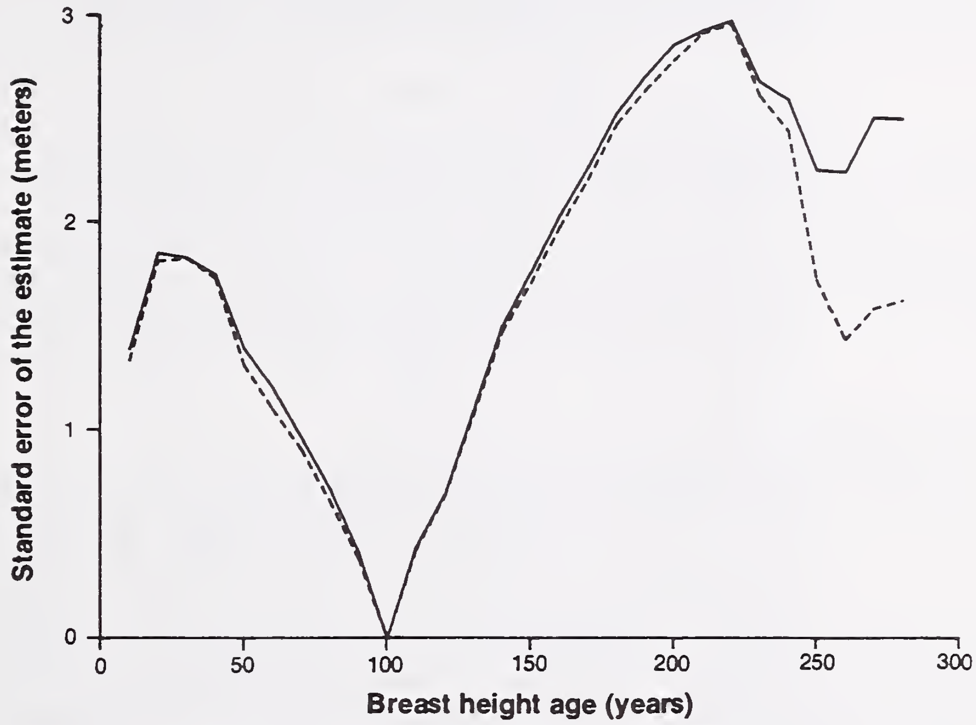

Figure 7.—Standard error of the estimate (uncorrected for the degrees of freedom in the models) for height growth models by decadal age. The solid line is for the final height growth model, equation (6), and the dashed line is for the regressions produced by Heger's (1968) method, equation (1).

Figure 8.—Standard error of the estimate (uncorrected for the degrees of freedom in the models) for site index models by decadal age. The solid line is for the final site index model, equation (14), and the dashed line is for the regressions produced by Heger's (1968) method, equation (7).

Reliability is reduced by use of the equations beyond the range of the data used to construct them. This range is indicated in figures 2 and 4. Note that no trees older than 139 years at breast height were found at high site indices (table 1). This is reflected in figures 2 and 4 by the jagged appearance of Heger's curves and their divergence from the final model curves at these ages and sites. As a result, estimates at advanced ages and high sites are relatively unreliable extrapolations.

The equations presented here have SEE's similar to those of Monserud (1984) for Douglas-fir in the northern Rocky Mountains, the only other Douglas-fir curves for which this statistic was found. Our SEE's for height growth equation (6) and site index equation (14) are 1.73 and 2.07 m, respectively; Monserud's "tree-about-the-model" errors are 1.55 and 1.89 m, respectively. When data for ages older than 200 years are excluded (as Monserud did), our SEE's (1.53 and 2.06 m) for dry-site Douglas-fir are even closer to his. We, however, included these data to provide a better basis for predictions at advanced ages, and because the data for these ages received low weights in the weighted regression procedure.

We considered Heger's linear equations (1) and (7) to provide the best possible fit, since there was no curvilinear relationship between site and height at any age. The uncorrected sums of squares for error (SSE) of the final models were similar to those for Heger's model (figs. 7 and 8) at all but the oldest ages. Better final models, therefore, could offer only slight improvement unless new variables (for example, soils, nutrients) were considered. We sampled a narrow range of plant communities: the range in site index (28.57 to 48.00 m), only 52 percent of the mean site index (37.31 m), is lower than that of other studies. Thus, environmental variables are unlikely to improve model fit.

Overfitting the data, constructing models that describe meaningless irregularities in the data, can be a problem when models are fit to small data sets such as this one of 27 trees. If this had occurred, it is reasonable to conclude that the SEE's would have been artificially low. The previous comparison with Monserud's (1984) SEE's, however, indicates that this probably did not occur.

Occasionally, straight boles, well-formed tops, and increment cores indicated no problems in height growth, but after the stems were dissected, height growth curves or portions thereof showing height growth suppression were excluded from the analysis. This will not be possible, however, in routine applications of these equations; in particular, estimates of site index for such trees will be low and estimates of height growth (when site index is known from other trees) will be high. Applications of the equations in young stands will not have this bias because all the rejected trees were 117 years at breast height or older. This problem is common (though seldom discussed) to all studies in which data are rejected based on examination of height growth curves after stem dissection. Examination of the height growth curves for trees rejected in this study indicates errors in site index and height will usually be less than 2-3 m.

This source of error will probably be more important in dry-site Douglas-fir communities, where potential site index trees often regenerate after wildfire in stands with surviving trees (Means 1982), and will be less important in community types that are usually even aged. Therefore site index may be less suitable as a productivity index, and the availability of growth models suited to uneven-aged, dry-site stands is probably more critical.

How To Use the Equations

The height growth and site index curves differ in form (fig. 5) and recommended use. The height growth equation was fit with height as the dependent variable. It describes the height growth of trees that attain a specified site index at index age and is appropriate for prediction of height and height growth for stands of given site index, as in construction of yield tables and in stand simulators. The site index equation was fit with site index as the dependent variable. It is a more efficient estimator of site index than is the height growth equation (Curtis and others 1974a) and should be used for estimating site index when age and height are known.

Stand Selection

These equations should be applied to stands in the Willamette National Forest in the Ranger Districts sampled (fig. 1). These equations may be more appropriate than other available equations for use in other Ranger Districts or in adjacent areas (for example, southwestern Oregon); this, however, is not certain. The error associated with this sort of extrapolation probably increases with distance from the areas sampled (fig. 1) and cannot be estimated from data at hand.

Stands should be in dry-site Douglas-fir, defined as Douglas-fir or incense-cedar climax and should lack a significant cover (0.1 percent) of western hemlock in any size class. The above comparisons with other curves indicate that the dry-site Douglas-fir curves are not appropriate for other communities.

Tree Selection

Site index estimates should be based on one or two (when possible) healthy dominants or strong codominants on each 0.1-ha (0.25-acre) plot. Boles should be straight and there must be no signs of past top damage. Candidate trees must be increment bored at breast height, and trees showing suppressed radial growth must be rejected. The desired precision of the site index estimate will determine the number of plots to be taken in a stand.

Top breakage and periods of suppression are likely to be common problems on dry sites where understory trees can eventually reach the canopy. When two acceptable trees occur on a plot, their site index estimates should be averaged. Acceptable site index trees are rare in stands with many trees older than about 200 years, so estimating the site index for these stands may be difficult.

Equations for Total Height in Feet

The following equations are in a form probably most useful to most people. The height growth equation, equation (6), in units of feet is,

$$HT = 4.5 + (SI\text{-}4.5) / (d + bA^{n} + e/(SI\text{-}4.5) + cA^{n}/(SI\text{-}4.5)); \qquad (15)$$

where HT = total height in feet, A = age at breast height (4.5 ft), SI = total height in feet at 100 yr, d = 0.90031, b = 36.932, e = -39.258, c = 14544.39, and n = -1.28438.

The site index estimating equation, equation (14), in units of feet is;

$$SI = 4.5 + 3.28084((b + cA + d/A^{0.5})(0.3048(HT\text{-}4.5) - 1/(e + fA^{g})) + k(HT\text{-}4.5) + j); \qquad (16)$$

where SI, HT, and A are defined as for equation (15), b = 0.94622, c = -0.00175322, d = 3.6660, e = 0.0168601, f = 2.7676, g = -1.19554, k = -0.041911, and j = 40.470.

Acknowledgments

We thank Robert O. Curtis, Robert A. Monserud, Miles A. Hemstrom, David Hann, and Robert Sanders for helpful reviews; Lewis Hass, Jack Booth, Dick Carkin, and Kevin Short for field assistance; and Rod Slagle for computer guidance.

English Equivalents

1 hectare = 2.47 acre
1 meter = 0.3048 foot
1 centimeter = 0.3937 inch

Literature Cited

Beck, Donald E. Height-growth patterns and site index of white pine in the southern Appalachians. Forest Science. 17: 252-260; **1971.**

Cochran, P. H. Site index and height growth curves for managed, even-aged stands of Douglas-fir east of the Cascades in Oregon and Washington. Res. Pap. PNW-251. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1979.**16 p.

Curtis, R. O. A stem analysis approach to site index curves. Forest Science. 10: 241-256; **1964.**

Curtis, Robert O.; Clendenen, Gary W.; DeMars, Donald J. A new stand simulator for coast Douglas-fir: DFSIM user's guide. Gen. Tech. Rep. PNW-128. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1981.** 79 p.

Curtis, Robert O.; Clendenen, Gary W.; Reukema, Donald L.; DeMars, Donald J. Yield tables for managed stands of coast Douglas-fir. Gen. Tech. Rep. PNW-135. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1982.** 182 p.

Curtis, Robert O.; DeMars, Donald J.; Herman, Francis R. Which dependent variable in site index-height-age regressions? Forest Science. 20: 74-87; **1974a.**

Curtis, Robert O.; Herman, Francis R.; DeMars, Donald J. Height growth and site index for Douglas-fir in high-elevation forests of the Oregon-Washington Cascades. Forest Science. 20: 307-316; **1974b.**

Dahms, Walter G. Correction for possible bias in developing site index curves from sectioned tree data. Journal of Forestry. 61: 25-27; **1963.**

Dahms, Walter G. Gross yield of central Oregon lodgepole pine. In: Baumgartner, David M., ed. Management of lodgepole pine ecosystems: Proceedings of a symposium. Pullman, WA: Washington State University, Cooperative Extension Service; **1975:** 208-232.

Dyrness, C. T.; Franklin, Jerry F.; Moir, W. H. A preliminary classification of forest communities in the central portion of the western Cascades of Oregon. Coniferous For. Biome Bull. 4. Seattle, WA: University of Washington, US/IBP; **1974.** 123 p.

Heger, L. A method of constructing site index curves from stem analyses. Forestry Chronicle. 44: 11-15; **1968.**

Herman, Francis R.; DeMars, Donald J.; Wollard, Robert F. Field and computer techniques for stem analysis of coniferous forest trees. Res. Pap. PNW-194. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1975.** 51 p.

King, James E. Site index curves for Douglas-fir in the Pacific Northwest. For. Pap. 8. Centralia, WA: Weyerhaeuser Company, Forestry Research Center; **1966.** 49 p.

McArdle, Richard E.; Meyer, Walter H.; Bruce, Donald. The yield of Douglas-fir in the Pacific Northwest. Tech. Bull. 201. Washington, DC: U.S. Department of Agriculture; **1961.** 74 p.

Means, Joseph E. Developmental history of dry coniferous forests in the western Oregon Cascades. In: Means, Joseph E., ed. Forest succession and stand development research in the Northwest: Proceedings of a symposium; 1980 March 26; Corvallis, OR. Corvallis, OR: Oregon State University, College of Forestry; **1982:** 141-158.

Means, Joseph Earl. Dry coniferous forests in the western Oregon Cascades. Corvallis, OR: Oregon State University; **1980.** 268 p. Ph.D. thesis.

Monserud, Robert A. Height growth and site index curves for inland Douglas-fir based on stem analysis data and forest habitat type. Forest Science. 30: 943-965; **1984.**

*GPO 596-739 1985

Means, Joseph E.; Helm, Mary E. Height growth and site index curves for Douglas-fir on dry sites in the Willamette National Forest. Res. Pap. PNW-341. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 17 p.

Equations and curves are presented for estimating height and site index of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) on hot, dry sites in the Willamette National Forest in western Oregon. The equations are based on the dissected stems of 27 trees. The curves differ from those previously published for Douglas-fir. Instructions are presented for their use.

Keywords: Increment (height), site index, Douglas-fir, Oregon (Willamette National Forest).

The **Forest Service** of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives — as directed by Congress — to provide increasingly greater service to a growing Nation.

Pacific Northwest Forest and Range
Experiment Station
319 S.W. Pine St.
P.O. Box 3890
Portland, Oregon 97208